

# Vector and axial-vector structures of the $\Theta^+$

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## Abstract

We present in this talk recent results of the vector and axial-vector transitions of the nucleon to the pentaquark baryon  $\Theta^+$ , based on the  $SU(3)$  chiral quark-soliton model. The results are summarized as follows:  $K^*N\Theta$  vector and tensor coupling constants turn out to be  $g_{K^*N\Theta} \simeq 0.81$  and  $f_{K^*N\Theta} \simeq 0.84$ , respectively, and the  $KN\Theta$  axial-vector coupling constant to be  $g_A^* \simeq 0.05$ . As a result, the total decay width for  $\Theta^+ \rightarrow NK$  becomes very small:  $\Gamma_{\Theta \rightarrow NK} \simeq 0.71$  MeV, which is consistent with the DIANA result  $\Gamma_{\Theta \rightarrow NK} = 0.36 \pm 0.11$  MeV.

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## I. INTRODUCTION

The pentaquark baryon  $\Theta^+$  has been one of the most important issues in hadron spectroscopy [1, 2] (See recent reviews, for example, Refs. [3, 4]). More recently, the CLAS experiments reported null results of the  $\Theta^+$  [5, 6, 7, 8], so that its existence has been doubted. On the other hand, the DIANA collaboration announced very recently the formation of a narrow  $pK^0$  peak with mass of  $1537 \pm 2$  MeV/ $c^2$  and width of  $\Gamma = 0.36 \pm 0.11$  MeV in the  $K^+n \rightarrow K^0p$  reaction [9]. Since several new experiments for the  $\Theta^+$  are under way [10, 11, 12], it is too early to conclude the absence of the  $\Theta^+$ . However, the total cross section for the  $\Theta^+$  photoproduction should be quite small, as already indicated from the CLAS results. The implications of these experimental results may be theoretically interpreted as small coupling strengths of  $K^*N \rightarrow \Theta^+$  and  $NK \rightarrow \Theta^+$  transitions. Thus, in the present talk, we will show that these coupling constants are actually very small, using the chiral quark-soliton model ( $\chi$ QSM).

## II. $K^*N \rightarrow \Theta^+$ AND $KN \rightarrow \Theta^+$ TRANSITION FORM FACTORS

The vector and axial-vector transition form factors of the  $N \rightarrow \Theta^+$  are defined in the following matrix elements:

$$\begin{aligned}\langle B_{\Theta^+} | \bar{u} \gamma_\mu s | B_N \rangle &= \bar{u}_{\Theta^+} \left[ \gamma_\mu F_1^*(Q^2) + i \frac{\sigma_{\mu\nu} q^\nu F_2^*(Q^2)}{M_N + M_{\Theta^+}} + \frac{q_\mu F_3^*(Q^2)}{M_N + M_{\Theta^+}} \right] u_N, \\ \langle B_{\Theta^+} | \bar{u} \gamma_\mu \gamma_5 s | B_N \rangle &= \bar{u}_{\Theta^+} \left[ \gamma_\mu g_1^*(Q^2) + i \frac{q_\mu g_2^*(Q^2)}{M_N + M_{\Theta^+}} + \frac{P_\mu g_3^*(Q^2)}{M_N + M_{\Theta^+}} \right] \gamma_5 u_N,\end{aligned}\quad (1)$$

where  $Q^2 = -q^2$  is the square of the four momentum transfer  $q^2 = (p - p')^2$  with positive definiteness in the space-like region. The  $M_{\Theta^+}$  and  $M_N$  denote the masses of the nucleon and  $\Theta^+$ , respectively. The  $\bar{u}_{\Theta^+}$  and  $u_N$  are the corresponding Dirac spinors, respectively. The  $q_\mu$  and  $P_\mu$  stand, respectively, for the four momentum transfer ( $q = p' - p$ ) and the sum of the momenta ( $P = p' + p$ ).  $F_i^*$  and  $g_i^*$  are, respectively, vector and axial-vector form factors that are real and functions of  $q^2$ . Since the mass difference between  $M_{\Theta^+}$  and  $M_N$  are not small, the  $F_3^*$  and  $g_3^*$  do not vanish. However, they do not play any important role in determining the coupling constants for the  $K^*N\Theta$  and  $KN\Theta^+$  vertices. In fact, the third form factor  $F_3^*$  in the vector channel is related to the scalar form factor, i.e. to the  $\kappa^*$  couplings.

In the vector channel, the time and space components of the current are directly related to the Sach-type form factors,  $G_E^*$  and  $G_M^*$  as follows:

$$\begin{aligned}\langle B_{\Theta^+} | \bar{u} \gamma_4 s | B_N \rangle &= G_E^*(q^2) \delta_{ss'}, \\ \langle B_{\Theta^+} | \bar{u} \gamma_k s | B_N \rangle &= \frac{i}{2M_N} \epsilon_{klm} (\sigma^l)_{ss'} q^m G_M^*(q^2).\end{aligned}\quad (2)$$

We will compute these two form factors  $G_E^*$  and  $G_M^*$ , and axial-vector transition form factors within the framework of the SU(3)  $\chi$ QSM. In the electric transitions, we find that  $G_E^*$  at  $Q^2 = 0$  is determined by the generalized Ademollo-Gatto (AG) theorem, i.e., it vanishes in the chiral limit but acquires a small contribution from the mixing angle between the octet and anti-decuplet representations or from the wave-function corrections:  $G_E^*(0) = \sqrt{3} c_{10}^n$ . The detailed formalism and results can be found in Ref. [13].

The  $K^*N\Theta^+$  vector and tensor coupling constants are determined by the vector meson dominance (VMD). Using the current-field identity

$$J_\mu^{4+i5} = \bar{u}\gamma_\mu s = \frac{m_{K^*}^2}{f_{K^*}} K_\mu^*, \quad (3)$$

where  $m_{K^*}$  denotes the mass of the vector meson  $K^*$ . The  $f_{K^*}$  stands for the generalized  $K^*$  meson coupling constant which can be determined from the  $\rho$  meson coupling constant, one can relate the electromagnetic transition form factors  $G_E^*$  and  $G_M^*$  to the  $K^*N\Theta^+$  vector and tensor coupling constants  $g_{K^*N\Theta^+}$  and  $f_{K^*N\Theta^+}$ . Note that the tensor coupling constant has been often neglected in the reaction calculations for the  $\Theta^+$  photoproduction [14, 15]. Ref. [16] has kept the tensor coupling constant finite but dropped out the vector coupling constant.

### III. RESULTS AND DISCUSSION

In this Section, we will briefly discuss the results of the coupling constants. In the following, we calculate them with the constituent quark mass  $M = 420$  MeV. The strange current quark mass is treated perturbatively, so that it is taken into account to linear order  $\mathcal{O}(m_s^1)$ . The  $m_s$  is selected to be  $m_s = 180$  MeV which is the best value for the mass-splitting.

We can extract the  $K^*N\Theta^+$  vector and tensor coupling constants from the  $K^*N \rightarrow \Theta^+$  electromagnetic transition form factors with the help of the VMD:

$$g_{K^*n\Theta} = f_{K^*} G_E^* \quad \text{and} \quad f_{K^*n\Theta} = f_{K^*} [G_M^* - G_E^*]. \quad (4)$$

Using the values of  $f_{K^*} \simeq 5.71$ , and of  $G_E^*$  and  $G_M^*$ , we can easily determine the  $K^*N\Theta^+$  vector and tensor coupling constants. Let us first determine the  $g_{K^*n\Theta}$  in the chiral limit. Since  $G_E^*$  at  $Q^2 = 0$  turns out to be zero due to the AG theorem, the  $g_{K^*n\Theta}$  becomes also zero as already mentioned in Ref. [17]. However, when the  $m_s$  corrections is switched on,  $G_E^*$  acquires the wave-function corrections, again, due to the AG theorem and we get :  $G_E^* \simeq 0.142$ . Thus, the  $K^*$  vector coupling constant becomes  $g_{K^*n\Theta} \simeq 0.81$ . On the other hand, the  $K^*$  tensor coupling constant is determined to be  $f_{K^*n\Theta} \simeq 2.91$  in the chiral limit, while with the flavor SU(3) symmetry breaking  $f_{K^*n\Theta} \simeq 0.84$ . This large difference can be understood by Eq.(4). The finite value of  $G_E^*$  due to the AG theorem gets  $f_{K^*N\Theta^+}$  decreased. The results in the chiral limit are consistent with those in Ref [17]. However, we want to emphasize on the fact that due to the AG theorem the vector coupling constant is about twice larger than the tensor one. The results are shown to be much smaller than those used in the reaction calculation [14, 15]. Moreover, a recent measurement for searching the  $\Theta^+$  via  $K^+p \rightarrow \pi^+X$  at the KEK concludes that either the  $K^*$ -exchange contribution should be excluded or  $g_{K^*n\Theta}$  should be quite small [18]. Thus, the present results are very much consistent with the KEK measurement. The present result is also compatible with the CLAS null results, since the total cross section of the  $\Theta^+$  photoproduction is measured and turns out very small.

The axial-vector constants of the nucleon have been very well reproduced in the  $\chi$ QSM [19]. Here, we extend the calculation for the axial-vector constants, including the baryon anti-decuplet, in particular, the  $\Theta^+$ . Taking into account the rotational  $1/N_c$  corrections, linear  $m_s$  corrections, and wave-function corrections, we obtain  $g_A^*$  for the  $\Theta^+ \rightarrow nK^+$ :

$g_A^* = 0.05$ , which is very small. This smallness of the axial-vector transition constant has very important implications, since it will predict a very small value of the  $\Theta^+ \rightarrow nK^+$  decay width. In fact, we get  $\Gamma_{\Theta^+ \rightarrow nK^+} = 0.36$  MeV. The total decay width of the  $\Theta^+$  then turns out to be  $\Gamma_{\Theta^+} = 0.71$  MeV. It is a remarkable result, since the decay width of the  $\Theta^+$  is believed to be below 1 MeV. Actually, the recent DIANA experiment measures  $\Gamma_{\Theta^+} = 0.36 \pm 0.11$  MeV, which is very close to our result.

#### IV. SUMMARY AND CONCLUSION

In this talk, we have presented recent results of the vector ( $K^*$ ) and axial-vector transition coupling constants, based on the chiral quark-soliton model with the help of the vector meson dominance. We have learned that the  $K^*N \rightarrow \Theta^+$  electric transition form factor  $G_E^*$  at  $Q^2 = 0$  is solely controlled by the generalized Ademollo-Gatto theorem. As a result, the  $K^*$  vector coupling constant turns out to be very small. The  $K^*$  tensor coupling constant is even about twice smaller than the vector coupling constant. The results are consistent with recent experimental data.

The axial-vector transition ( $\Theta^+ \rightarrow nK^+$ ) coupling constant has been also presented. Its result is very small and leads to a tiny value of the  $\Theta^+$  total decay width. It is again consistent with the recent DIANA data.

The detailed works on the axial-vector transition form factors for the  $\Theta^+$  will soon appear elsewhere.

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- [1] D. Diakonov, V. Petrov, and M. V. Polyakov, Z. Phys. A **359**, 305 (1997).
  - [2] T. Nakano *et al.* [LEPS Collaboration], Phys. Rev. Lett. **91**, 012002 (2003).
  - [3] K. H. Hicks, Prog. Part. Nucl. Phys. **55**, 647 (2005) and references therein.
  - [4] K. Goeke *et al.*, Prog. Part. Nucl. Phys. **55**, 350 (2005), and references therein.
  - [5] M. Battaglieri *et al.* [CLAS Collaboration], arXiv:hep-ex/0510061.
  - [6] B. McKinnon *et al.* [CLAS Collaboration], Phys. Rev. Lett. **96**, 212001 (2006).
  - [7] S. Niccolai *et al.* [CLAS Collaboration], Phys. Rev. Lett. **97**, 032001 (2006).
  - [8] R. De Vita *et al.* [CLAS Collaboration], Phys. Rev. D **74**, 032001 (2006).
  - [9] V. V. Barmin *et al.* [DIANA Collaboration], Phys. Atom. Nucl. **70**, 35 (2007).
  - [10] T. Hotta [LEPS Collaboration], Acta Phys. Polon. B **36**, 2173 (2005).

- [11] K. Miwa *et al.* [KEK-PS E522 Collaboration], arXiv:nucl-ex/0601032.
- [12] T. Nakano, in this proceeding.
- [13] T. Ledwig, H.-Ch. Kim and K. Goeke, arXiv:0803.2276 [hep-ph].
- [14] Y. s. Oh, H. c. Kim and S. H. Lee, Phys. Rev. D **69**, 014009 (2004).
- [15] S. I. Nam, A. Hosaka and H.-Ch. Kim, J. Korean Phys. Soc. **49**, 1928 (2006).
- [16] H. Kwee et al., Phys. Rev. D **72**, 054012 (2005).
- [17] Y. Azimov et al., Phys. Rev. D **75**, 054014 (2007).
- [18] K. Miwa *et al.*, arXiv:0712.3839 [nucl-ex].
- [19] A. Silva, H.-Ch. Kim, D. Urbano and K. Goeke, Phys. Rev. D **72**, 094011 (2005).